

A Microphone-Array-Based System for Restoring Sound Localization with Occluded Ears

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ABSTRACT

Current helmets and hearing protectors interfere with the sound transmission to the ears and therefore affect the perception and localization of speech and other useful sounds. This can be a serious drawback especially when the person wearing the protection has to operate in complex, unpredictable environments. A novel electro-acoustic system for sound pass-through was developed that can make hearing protection acoustically 'transparent'. By using external microphone arrays tuned to have a directional sensitivity similar to that of the open ears, the system can not only improve audibility of low-level sounds but also restore normal sound localization. The tuning was done by selecting specific microphone positions and by designing digital filters through which the individual microphone signals are passed. The system was evaluated in a sound localization experiment. Two versions were tested: one with individualized digital filters and one with universal (generic) filters. A comparison was made with a system with single external microphones, and with an earmuff with no sound pass-through. An open-ear condition was included as reference. Results show that, across all occluded-ear conditions, localization performance is best for the microphone-array system with individualized digital filters. Compared to listening through passive earmuffs, the percentage of confusions (quadrant errors) is nearly halved. However, localization performance is still not as good as with open ears.

1 INTRODUCTION

An important disadvantage of almost any type of hearing protection is that it suppresses all sounds, not only the noise, so that it interferes with the perception of speech and other useful sounds. Especially in critical situations (e.g. a soldier fighting in an urban environment, with a threat of snipers) this can be an important drawback. Several hearing protectors that are currently on the market address this problem, by including a controlled acoustic leak (pass-through) that restores the audibility of low-level sounds, while blocking the harmful high-level sounds. The pass-through can be realized either with a non-linear acoustic filter, or with an electro-acoustic system, consisting of a microphone, amplifier, limiter and telephone. However, these systems only solve part of the problem. Hearing protectors do not only decrease the level of the incoming sound – resulting in a reduced audibility – but they also distort the sound field, which has a severe effect on the capability to localize sounds (Smootenburg & Geurtsen, 1991; Abel, 1996; Vause &

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Grantham, 1999; Bolia et al., 2000; Bolia & McKinley, 2000). The latter effect is not compensated for by existing systems with a pass-through.

In order to address this issue a system was developed that uses microphone arrays instead of single microphones (Bronkhorst, 2002). This system can restore both audibility and directional hearing because the microphone array not only picks up the external sounds – just as a single microphone does – but is also able to simulate the direction- and frequency-dependent acoustic properties of the open ear. The simulation is realized by optimizing the placement of the microphones and by passing the output signals of each microphone through a specially designed digital filter, before they are added.

The system developed by Bronkhorst (2002) has only 2 microphones per array and is therefore not capable of simulating directional dependencies outside the plane passing through the microphones. In the current study, an improved version was developed that has arrays with 3 microphones placed on the corners of an equilateral triangle. The system was evaluated in a sound localization experiment. Localization performance was measured for passive hearing protection and for hearing protection equipped with either single microphones or microphone arrays, using open-ear performance as reference. The system was also subjected to an acoustical validation.



Figure 1: Setup for measuring head-related transfer functions

2 SYSTEM DESCRIPTION

The fundamental idea underlying the design of the microphone array system is that directional hearing can be restored when the acoustical effects of the head, ears and body on incoming sounds are simulated. The main effects are the differences in level and arrival time between the two ears and the spectral features (i.e. the frequency-dependent amplification and attenuation of the sound) present at each ear (e.g. Kuhn, 1987). It is thought that the interaural differences mainly code the left-right dimension, whereas the spectral features code both the up-down and front-back dimensions. The acoustical effects can be represented mathematically by the complex-valued transfer functions from a sound source to both eardrums – the so-called head-related transfer functions (HRTFs; see e.g. Wightman and Kistler, 1989). The HRTFs used in the current study were measured with small Sennheiser KE 4-211-2 microphones placed in ear plugs completely sealing the ear canals. Subjects were seated in the center of a hoop on which a trolley with a loudspeaker was mounted (see Fig. 1). Movements of the hoop and loudspeaker were controlled by a PC.

Measurements were done for about 1000 source positions, which cover the sphere around the subject's head almost completely (except for positions with elevations more than 60° below the horizontal plane) with a resolution of $5\text{-}6^\circ$.

In order to simulate the HRTFs with microphone arrays it is first necessary to measure the transfer functions of the microphones themselves. This was also done in the facility shown in Fig. 1. The hearing protector with the microphone arrays was placed on a Head Acoustics HMS II artificial head which was positioned in the center of the hoop. The microphone transfer functions are quite different from HRTFs because they contain less spectral features. In order to make the microphone transfer functions similar to the HRTFs, the microphone signals are passed through digital filters, added, and then presented through telephones mounted inside the hearing protector, as indicated schematically in Fig. 2. The system used in this study consists of two arrays of 3 microphones placed on the outside of a Peltor H7A earmuff, custom-built pre-amplifiers, a PC with an RME Hammerfall audio device and two Sony MDR CD 999 telephones mounted inside the earmuffs. The audio device does the A/D and D/A conversion and has a telephone amplifier. The digital filtering is performed by a custom-made Delphi program running on the PC.

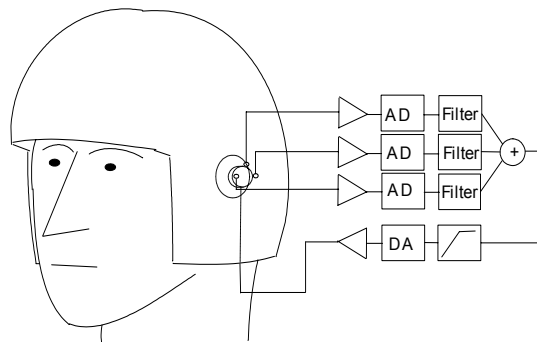


Figure 2: Schematic diagram of the microphone array system

The digital filters were calculated using software that minimizes the differences between the HRTFs and the transfer functions of the microphone array. Because digital filters are used, the filter characteristics only need to be determined at discrete signal frequencies. This means that six coefficients (two per filter) should be determined for each frequency. The calculation was done by iteratively minimizing a difference measure, which was the weighted sum of log-amplitude differences and group delay differences, averaged over angle of incidence. A set of 500 angles of incidence was used that covered the horizontal band with elevations between -22.5° and $+22.5^\circ$. In order to compensate for the characteristics of the telephones in the earmuffs, the calculated filter was multiplied by the inverse of the telephone transfer function. This was done separately for each ear.

3 EVALUATION

3.1 Design of the listening experiment

The effects of the presence or absence of hearing protection, and the type of pass-through were tested in the following five conditions:

1. open ears
2. earmuffs with the electronics switched off
3. earmuffs with a single microphone operating on each side

4. earmuffs with the microphone arrays and individualized filters
5. earmuffs with the microphone arrays and generic filters

Condition 1 was always presented first; the order of the other conditions was balanced across subjects. In these conditions, subjects wore the Peltor earmuffs equipped with the microphone arrays. The arrays were only switched on conditions 4 and 5; in condition 3, only the front microphone of the array was used and no digital filtering was performed. The individualized filters were calculated by fitting the transfer function of the array to the HRTFs of the listener, and by subsequently multiplying the filters by the inverse of the telephone transfer functions that had also been measured individually. The generic filters were based on HRTFs of one particular subject (not taking part in this study) which have proved to be suitable for many listeners. The inverse telephone transfer function was in this case the average of all individually measured transfer functions.

Table 1: Source positions used in the sound localization experiment

Azimuth Elevation	-180	-135	-120	-90	-45	-30	0	45	60	90	135	150
-45					X						X	
-30	X						X					
-20				X								
0	X		X			X	X		X	X		X
30	X			X			X					
45		X						X				
60	X						X			X		
90							X					

The experiment was conducted using the same setup as used for the HRTF measurements. Eight normal-hearing listeners were used as subjects. They were blindfolded, seated on an adjustable chair, and positioned so that their head was in the center of the hoop. Listeners indicated the perceived sound direction using a pointer (a small stick that could be rotated and tilted). In order to prevent confounding of perceived direction and distance, they were instructed not to set the pointer in the direction of the source, but to align it to the imaginary line between their head and the perceived source position.

Twenty-one loudspeaker positions were used (see Table 1); 9 positions were located in the median plane (the symmetry plane of the head), 6 in the right hemisphere, and 6 in the left hemisphere. Stimuli were 500-ms burst of pink noise with level of 75 dBA, measured at the position of the center of the listener's head. When the sound pass-through was switched off (condition 2), the level was increased by 10 dB. In each condition, 42 stimuli were presented (two per position); the order of the positions was randomized.

3.2 Results of the experiment

From the raw data, three different measures were determined: horizontal error, vertical error and percentage of confusions. All measures were derived from the directions of vectors pointing to the target and response (denoted as target and response vector, respectively). In order to calculate the horizontal error, the target vector was first rotated so that it had the same elevation as the response vector. The error was then taken as the angle between the response vector and the rotated target vector. The vertical error was taken simply as the difference in elevation between target and response vectors. A response was counted as a confusion when the angle between target and response vector was reduced by at least 30° after the response vector was mirrored in either the horizontal or the vertical plane passing through both ears (this corresponds to up/down and front/back confusions, respectively). Because confusions were resolved before the horizontal and vertical errors were calculated, there is a trade-off between confusions

and directional errors: any response that is not counted as confusion will cause an increase of one of the directional errors. This means that the choice of criterion for counting confusions is, to a degree, arbitrary, because it does not affect the sensitivity of the overall analysis.

Mean results and standard errors for the three measures are listed in Table 2. It can be seen that performance with open ears is clearly better than that with occluded ears, irrespective of the presence and type of sound pass-through. In order to verify this conclusion, we conducted, for each of the three measures, a single-factor repeated-measures ANOVA. A highly significant effect of condition was found in all cases, and Tukey HSD post-hoc analysis showed that the results of the open-ear condition were indeed significantly better than those for the other conditions ($p < 0.0001$). In the further analysis, we focused on the conditions with hearing protection, and we performed similar ANOVA's, excluding the data for the open-ear condition. In this analysis, we only found significant effects of condition on vertical error ($p = 0.025$) and percentage of confusions ($p = 0.008$) but not on horizontal error ($p = 0.24$). Tukey HSD post-hoc analysis revealed that the effects were due to the better performance when using microphone arrays with individualized filters (condition 4). There was a trend that the use of arrays with non-individualized filters (condition 5) also improved performance, but this effect did not reach the 5% significance limit.

Table 2: Results of the sound localization experiment. For each condition, the horizontal error, the vertical error, and the percentage of confusions are listed. Both mean values and standard errors are given.

Condition	Horizontal error (°)	S.e. (°)	Vertical error (°)	S.e. (°)	% confusions	S.e.
1 (open ears)	9.3	0.9	15.2	1.2	6.3	1.3
2 (passive muff)	18.6	1.5	26.7	0.6	35.1	4.2
3 (1 microphone)	16.1	1.4	26.6	0.8	32.1	2.5
4 (individualized)	15.8	0.9	23.3	1.4	20.2	2.4
5 (generic)	17.6	1.7	24.0	0.7	26.8	3.2

3.3 Acoustical measurements

Acoustical measurements were carried out to check the similarity between the transfer functions of the microphone array system and different sets of HRTFs. The earmuff with the microphone arrays was placed on the Head Acoustics artificial head, which was positioned in the center of the loudspeaker hoop. The microphone signals were amplified and passed through the digital filters calculated for one of the subjects; these were, in this case, not multiplied by the inverse telephone transfer function. Transfer function measurements were performed for the same set of directions as used in the earlier measurements: about 500 angles of incidence, with elevations between -22.5° and $+22.5^\circ$.

In the analysis, the results of the measurements were compared with the HRTFs on which the filters were based. Separate comparisons were carried out for amplitude and phase. The amplitudes were converted to dB and differences were averaged over frequency and angle of incidence. Only the first 124 bins were included in the averaging (corresponding approximately to the frequency range 100 Hz – 12 kHz). The phase of each measurement or HRTF was unwrapped, converted to time and then averaged, resulting in an average group delay. Because high-frequency delays are less relevant and possibly distorted by inaccurate unwrapping, this calculation was only based on bins 1-30 (roughly 100 Hz – 3 kHz). The comparison was repeated for all sets of HRTFs (also the 'generic' set), in order to see how effective the adaptation of the filters to specific HRTFs is. It appears that the match between the transfer functions of the microphone array system and the HRTFs is, indeed, optimal for the HRTFs on which the filter calculation was based. The average difference in amplitude is in that case 4.1 dB, whereas values between 4.8 and 5.6 dB are obtained for the other HRTF sets. Although the group delay differences depend less on HRTF set than the

amplitude differences, the difference was also smallest (0.06 ms) for the HRTF set on which the filters were based. Differences for the other sets ranged from 0.07 to 0.11 ms.

4. CONCLUSION

This study describes the development and evaluation of a microphone-array-based system that can be used to improve sound perception and localization of persons wearing hearing protection. The system uses arrays of 3 microphones placed on the shells of standard earmuffs, applies digital filtering to the microphone signals and presents the resultant signals through telephones mounted inside the shells. A listening experiment demonstrates that the system can significantly improve sound localization, compared to performance with passive earmuffs. The most notable effect is a reduction of the number of quadrant errors (confusions) from 35% to 20%. However, localization performance is still worse than that achieved with open ears (6% confusions). This means that we must look at how the system can be further improved, for example by increasing the number of microphones and by optimizing the placement of the microphones.

Interestingly, the subjective differences between listening with open ears and through the microphone array system are smaller than the localization experiment suggests. Other factors play a role as well, in particular the reproduction of background noise, which sounds much more natural through the microphone array than through single microphones or passive earmuffs. This can be explained by the fact that single microphones are not directional while the microphone arrays (like open ears) are most sensitive to sounds coming from frontal-lateral directions. The difference in global directional sensitivity will particularly have effects on sound perception in noisy environments and should be tested in separate (e.g. speech intelligibility) experiments.

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